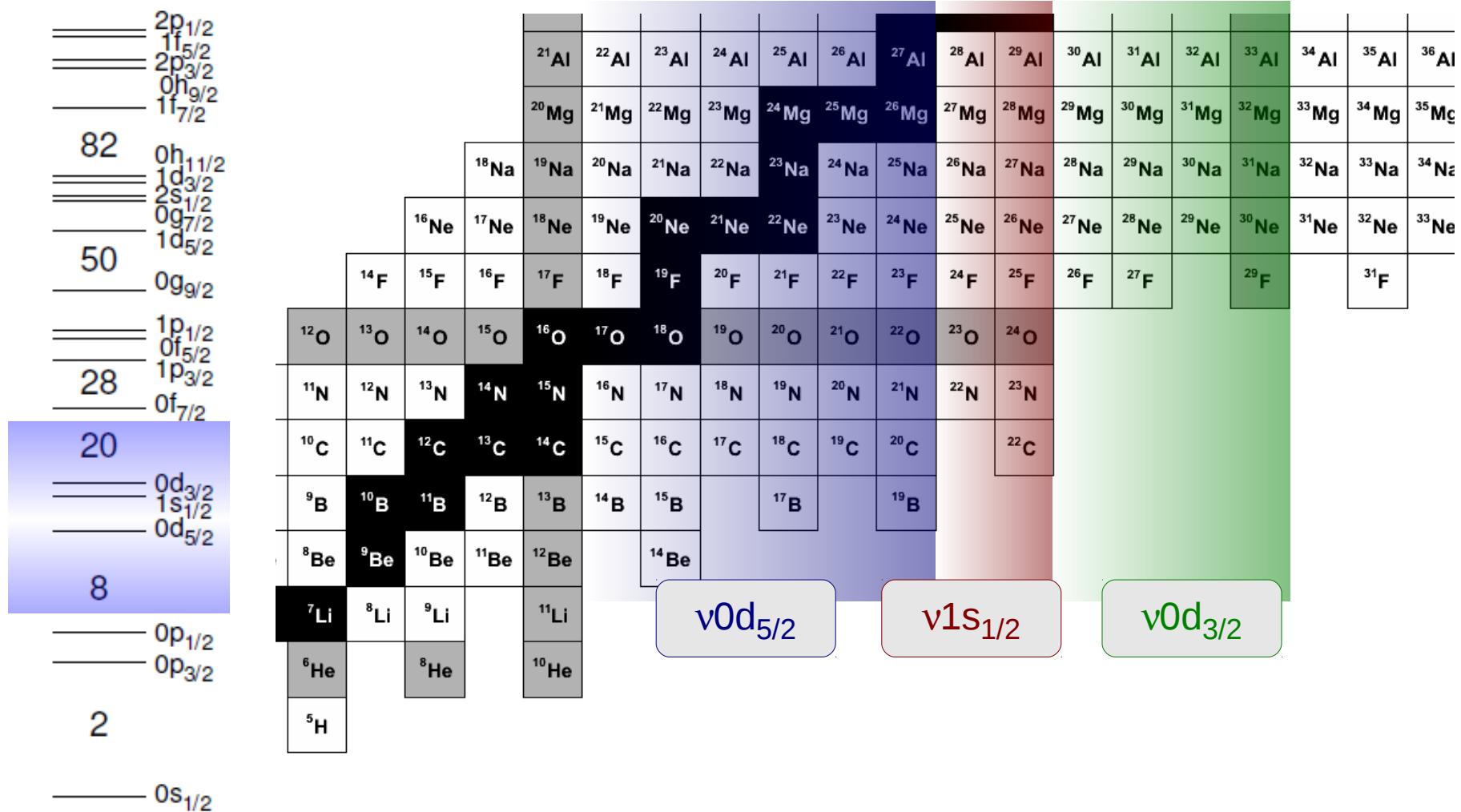


# On the evolution of the neutron $0d_{5/2}$ and $1s_{1/2}$ orbitals in neutron- rich $0p$ - $1s$ $0d$ shell nuclei

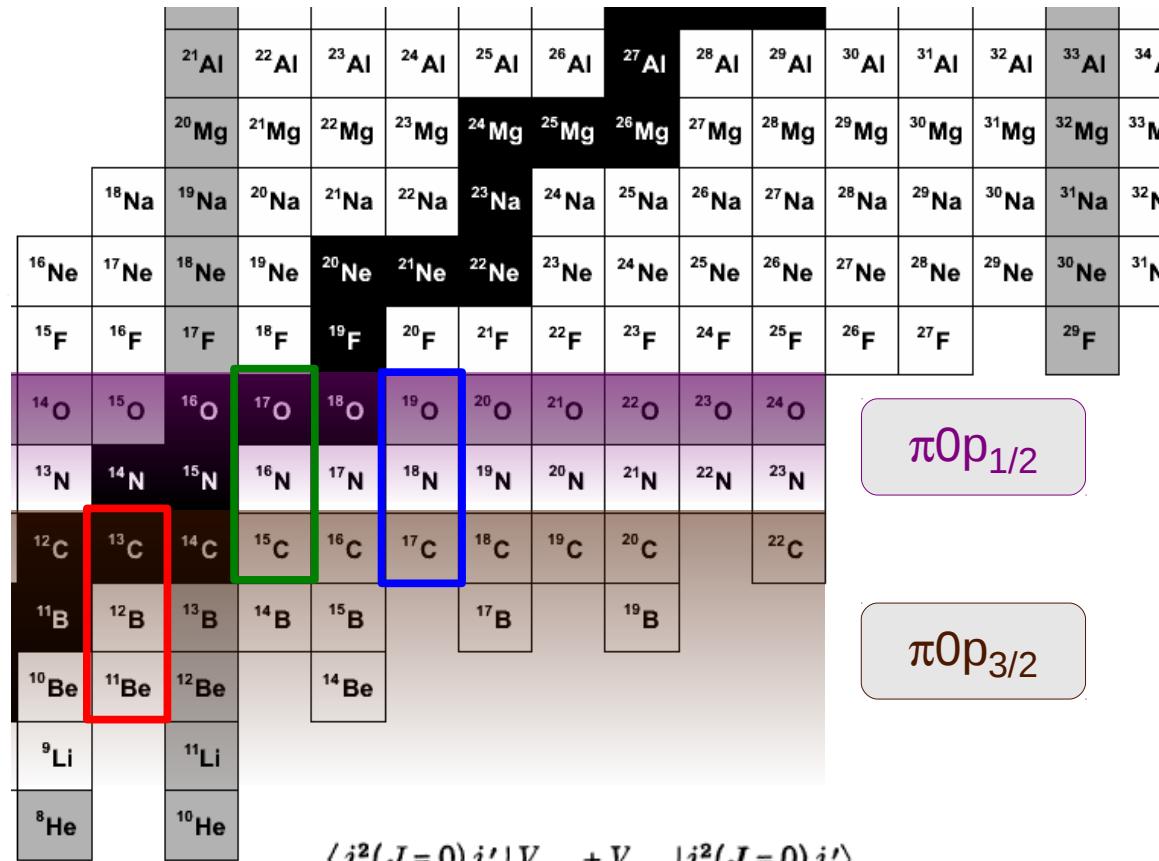
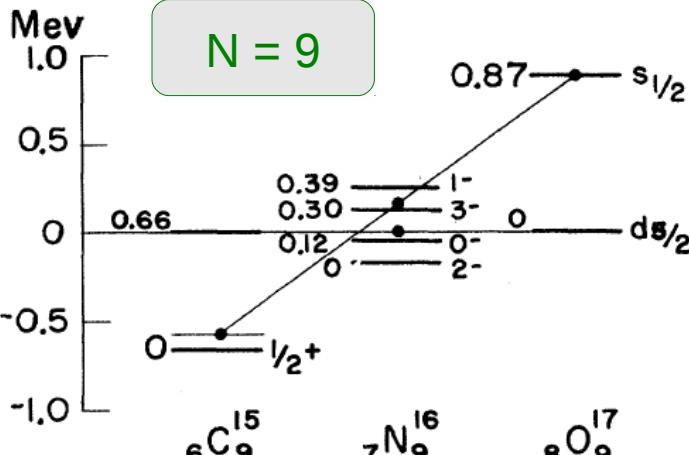
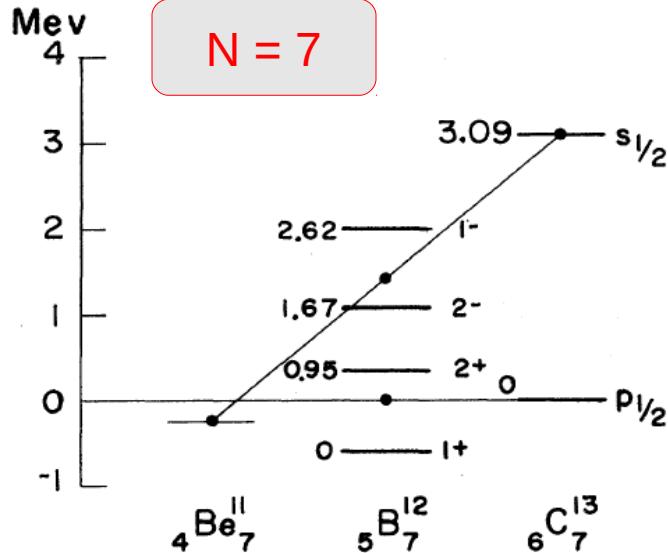
Calem R. Hoffman  
Argonne National Laboratory

Nuclear Structure 2012

# The neutron *sd* shell region ( $N = 9 - 20$ )



# Single-particle evolution across isotones



$\pi 0 p_{1/2}$

$\pi 0 p_{3/2}$

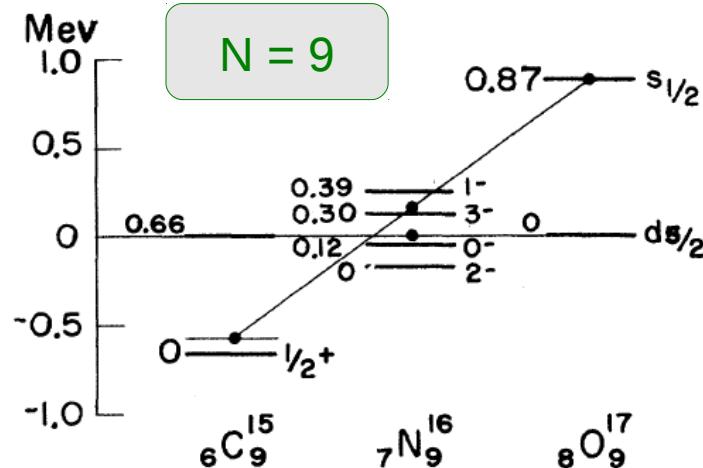
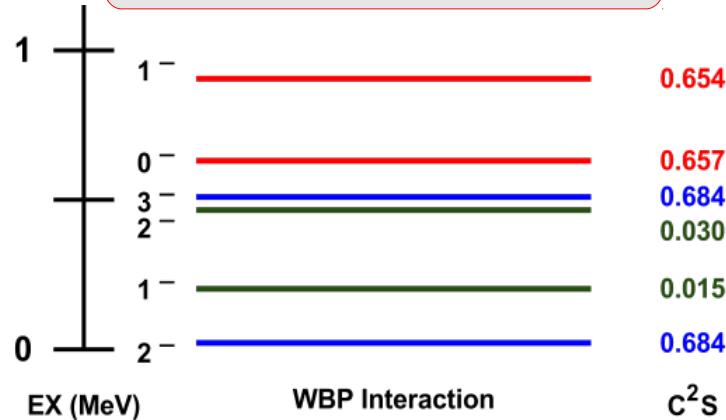
$$\langle j^2(J=0)j' | V_{1n} + V_{2n} | j^2(J=0)j' \rangle$$

$$= 2 \sum_{J=|j-j'|}^{J=j+j'} (2J+1) \langle jj'J | V | jj'J \rangle \left/ \sum_{J=|j-j'|}^{J=j+j'} (2J+1) \right. \quad (1)$$

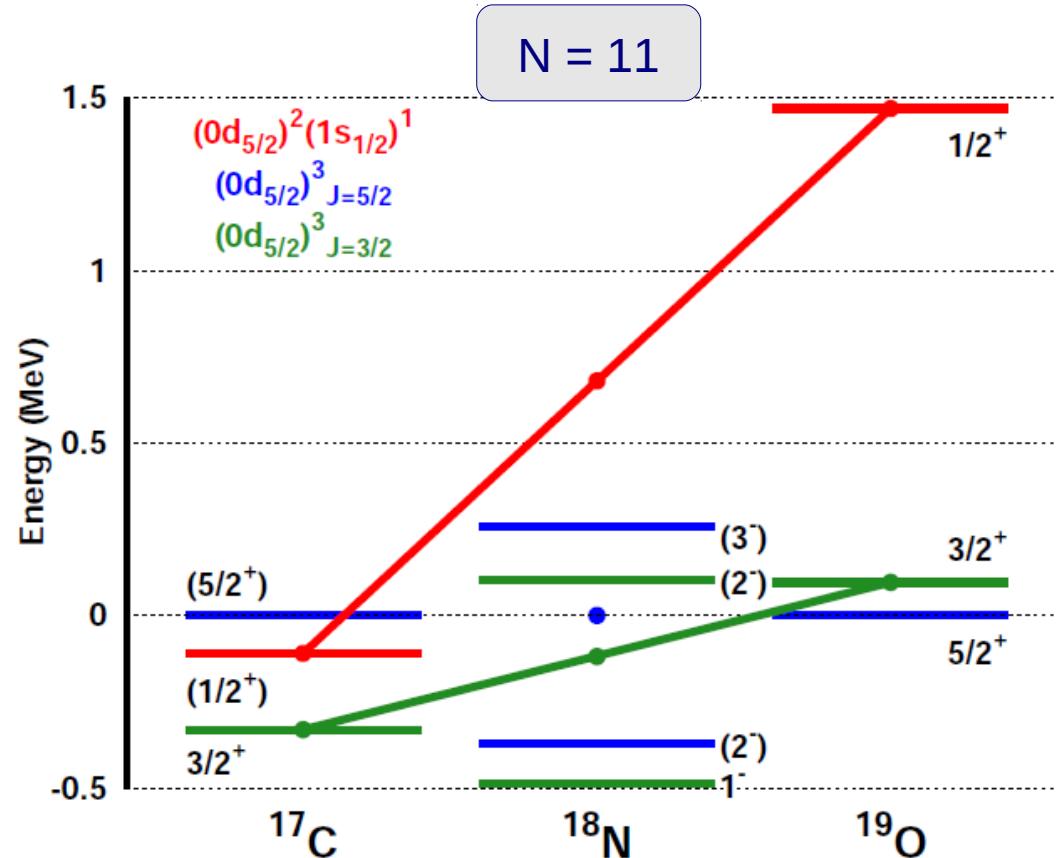
I. Talmi and I. Unna, PRL 4, 469 (1960)

# Single-particle evolution across isotones

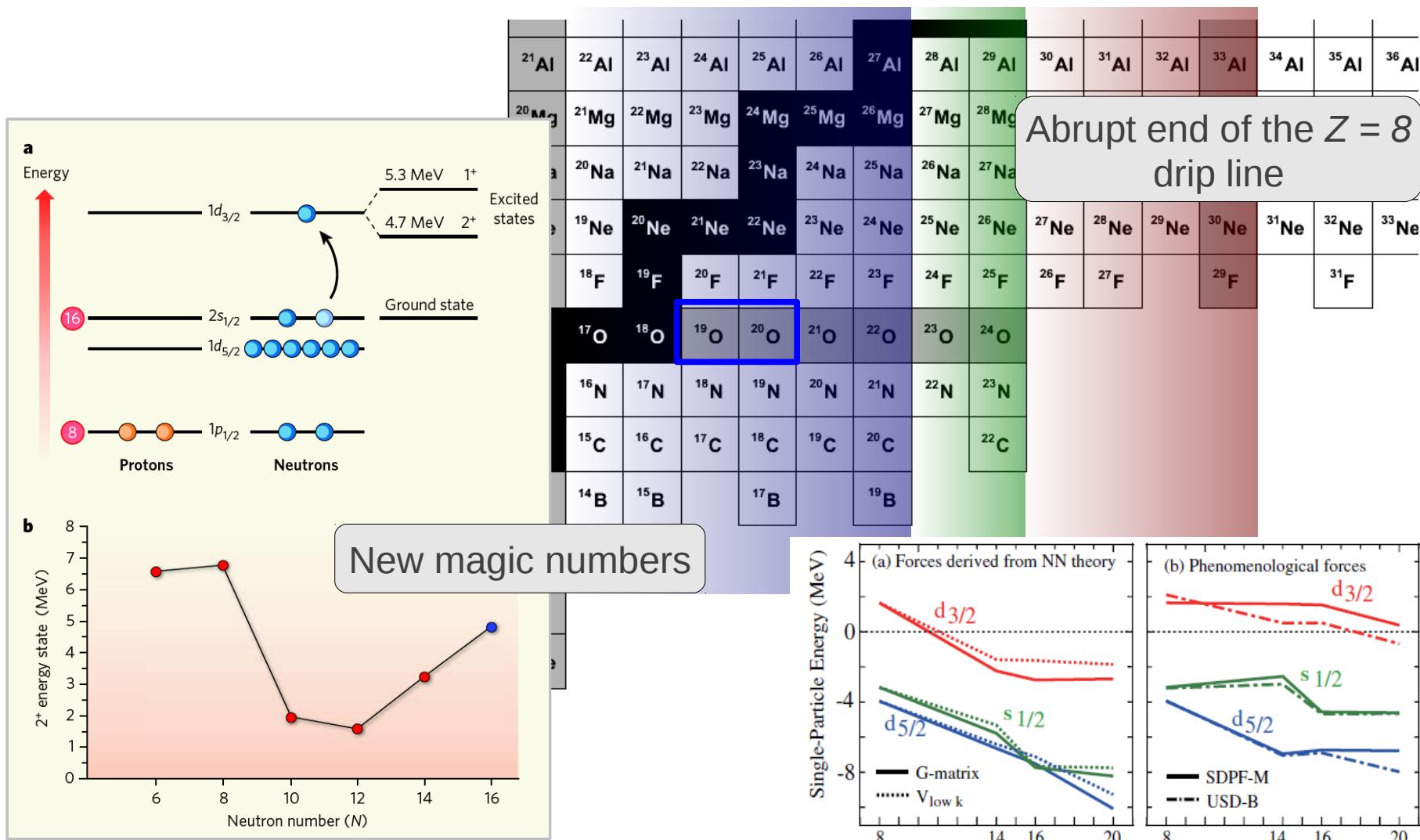
p-sd SM Calculations



I. Talmi and I. Unna, PRL 4, 469 (1960)



# Single-particle evolution along $Z = 8$

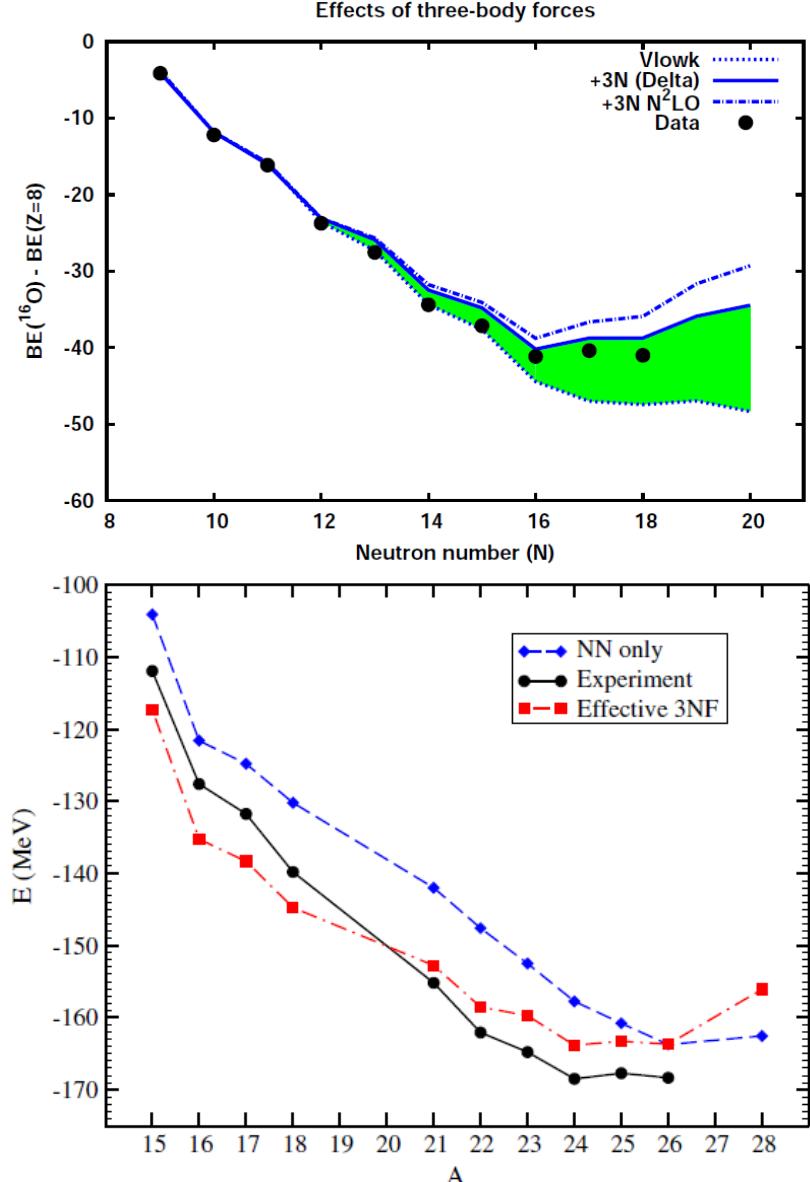
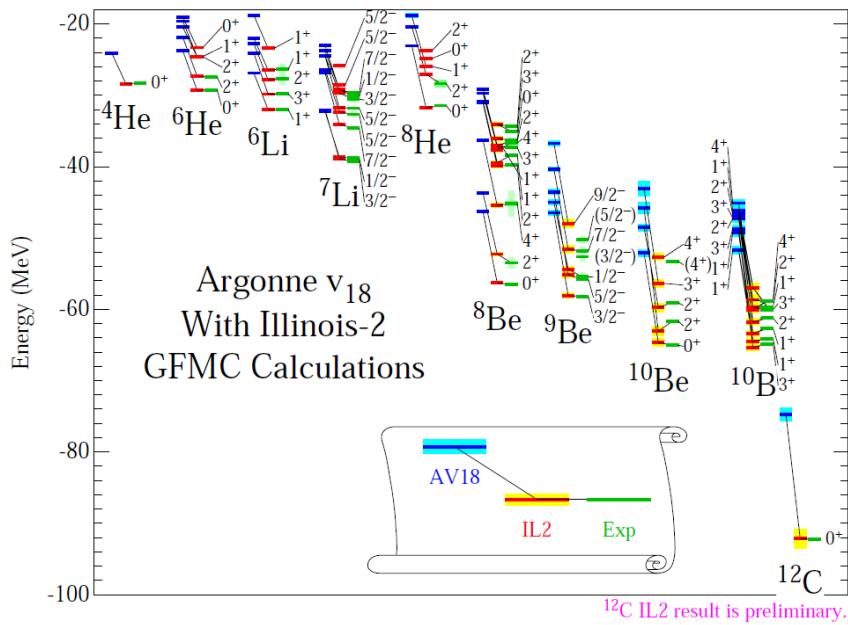


R. V. F. Janssens, Nature (London) 459, 1069 (2009)

Calem R. Hoffman – Argonne National Laboratory

H. Sakurai et al., PLB 448, 180 (1999)  
S. M. Lukyanov et al., Phys. At. Nucl. 67, 1627 (2004)

# Inclusion of three nucleon forces



- Increased ground state binding
  - GFMC & Coupled Cluster Calculations
- Reduced binding relative to <sup>16</sup>O core
- Impact of scattering into the continuum

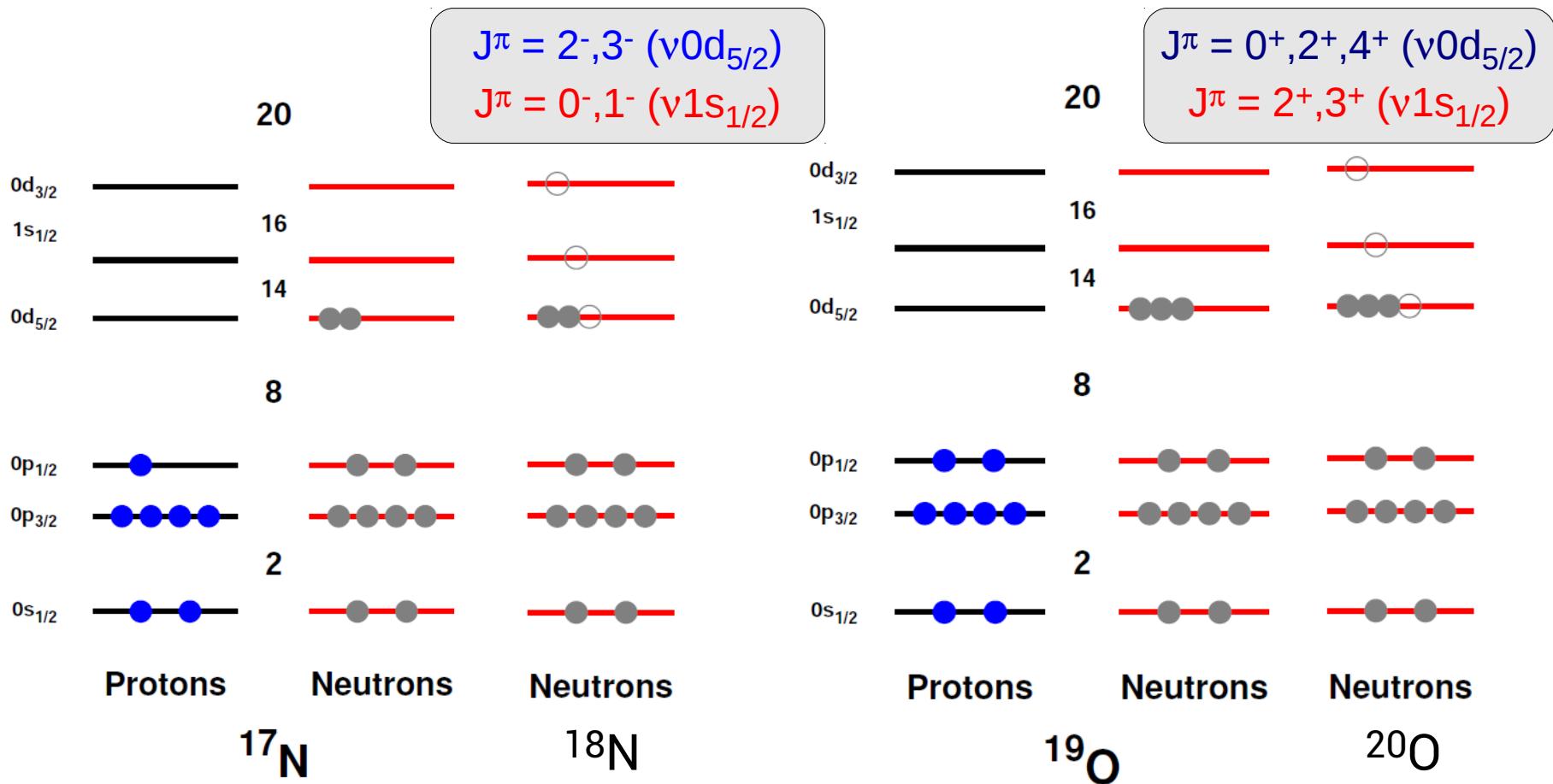
S. C. Pieper and R. B. Wringa, Annu. Rev. Nucl. Part. Sci. 51, 53 (2001)

T. Otsuka et al., PRL 105, 032501 (2010)

G. Hagen et al., PRL 108, 242501 (2012)

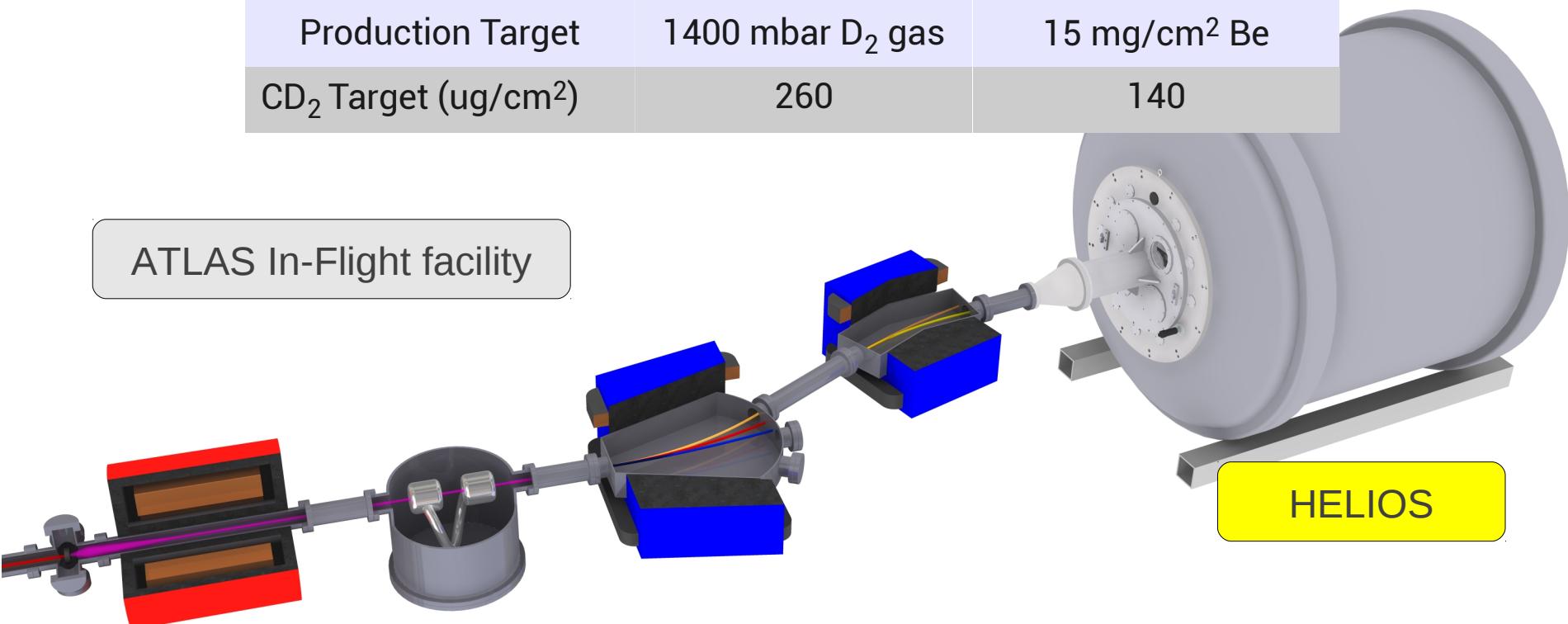
# Location of the $1s_{1/2}$ - $0d_{5/2}$ neutron orbitals

- Neutron adding ( $d,p$ ) reaction
  - $^{19}\text{O}(d,p)^{20}\text{O}$  – neutron  $sd$  orbitals as a function of N
  - $^{17}\text{N}(d,p)^{18}\text{N}$  – neutron  $sd$  orbitals as a function of Z



# Experimental details

Reaction	$^{19}\text{O}(\text{d},\text{p})^{20}\text{O}$	$^{17}\text{N}(\text{d},\text{p})^{18}\text{N}$
RIB Beam:	$^{19}\text{O}$	$^{17}\text{N}$
Energy (MeV/u)	6.9	13.5
Rate (pps)	$>10^5$	$>10^4$
Production Target	1400 mbar D <sub>2</sub> gas	15 mg/cm <sup>2</sup> Be
CD <sub>2</sub> Target (ug/cm <sup>2</sup> )	260	140



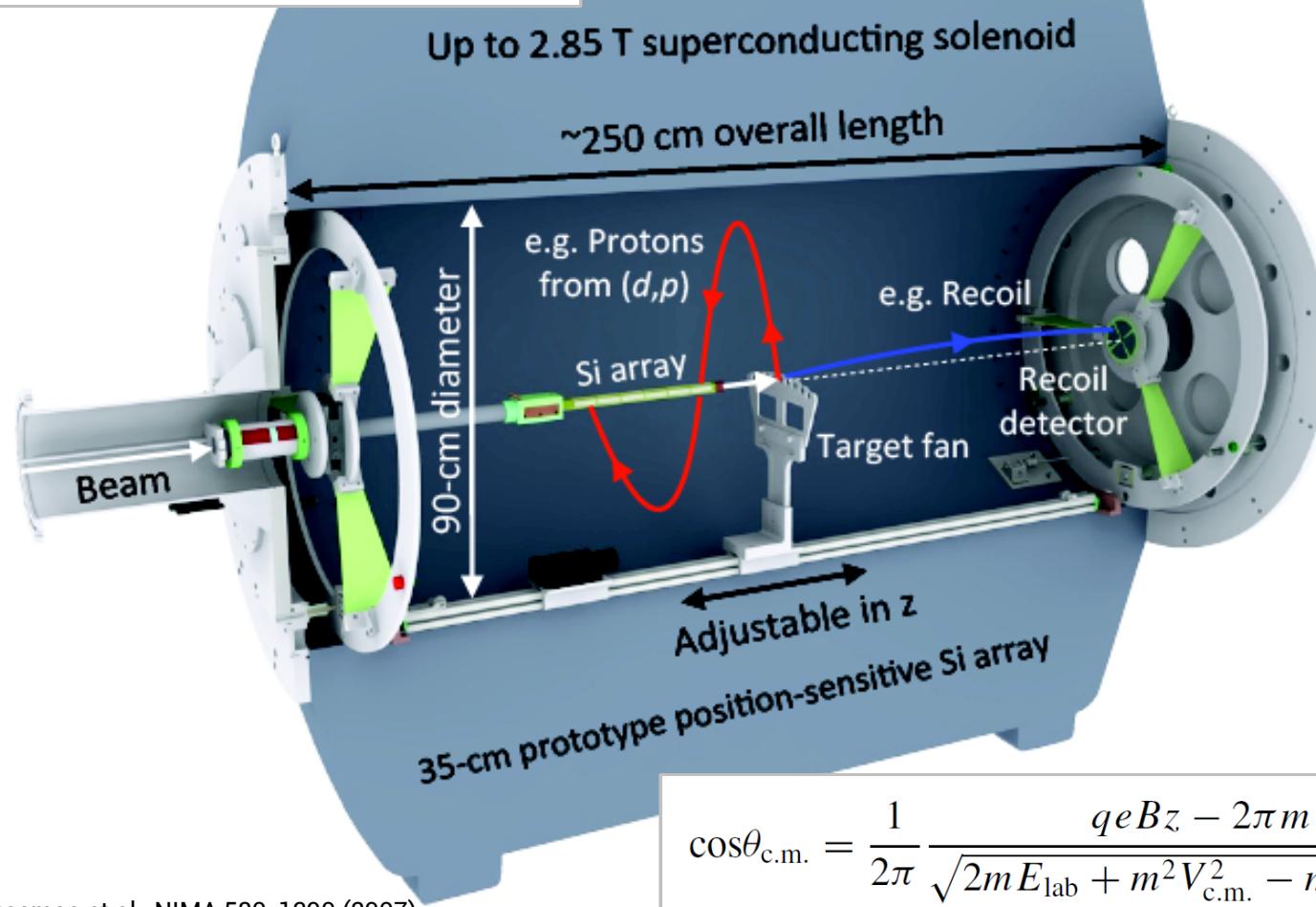
B. Harss et al., Rev. Sci. Instrum. 71, 380 (2000)

# HELIcal Orbit Spectrometer (HELIOS)



$$E_{\text{lab}} = E_{\text{c.m.}} - \frac{m}{2} V_{\text{c.m.}}^2 + \frac{m V_{\text{c.m.}} z}{T_{\text{cyc}}}.$$

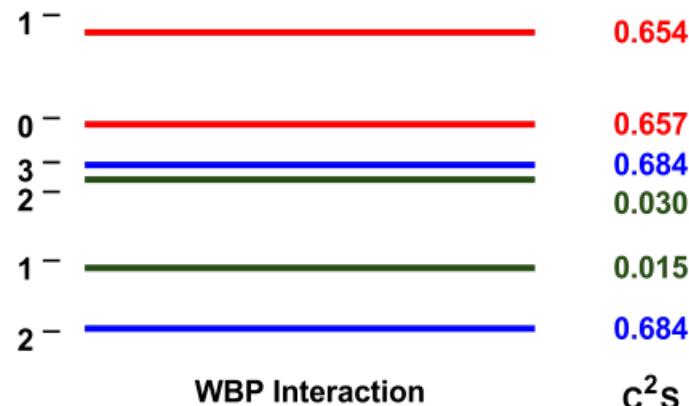
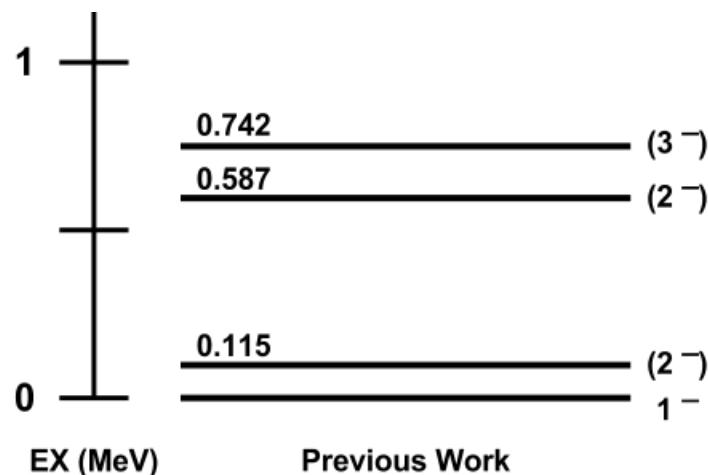
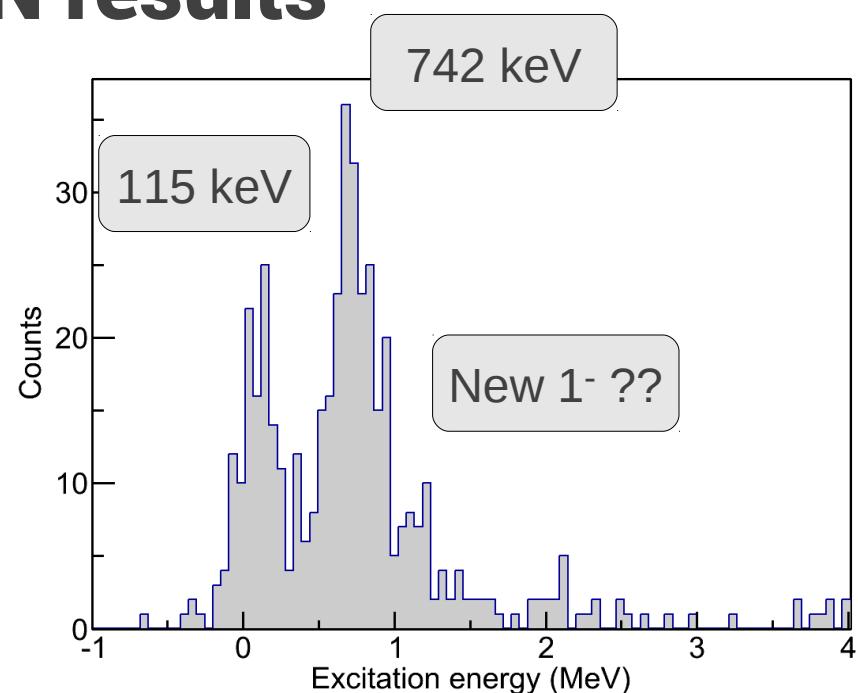
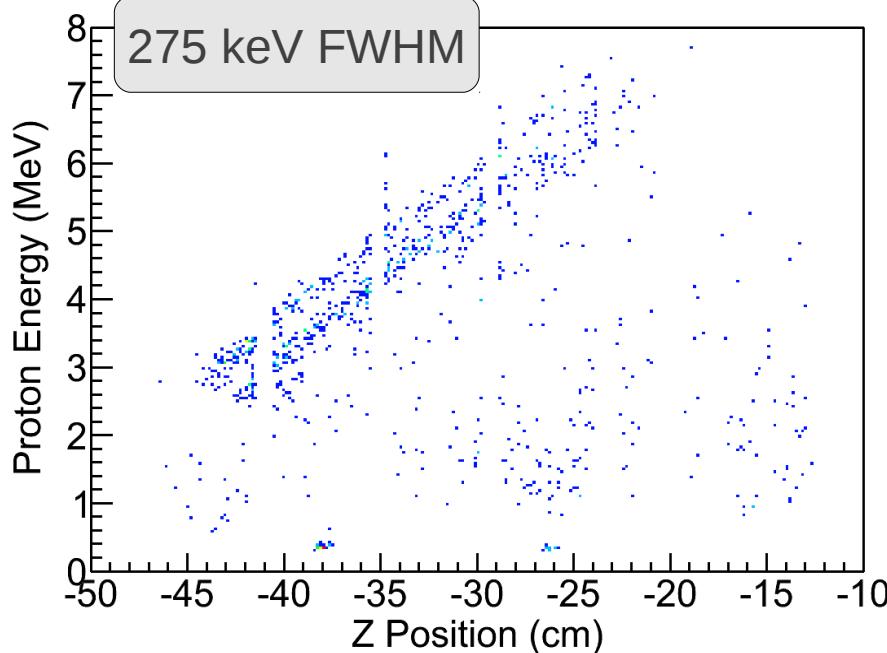
$$T_{\text{cyc}} = \frac{2\pi}{B} \frac{m}{qe}.$$



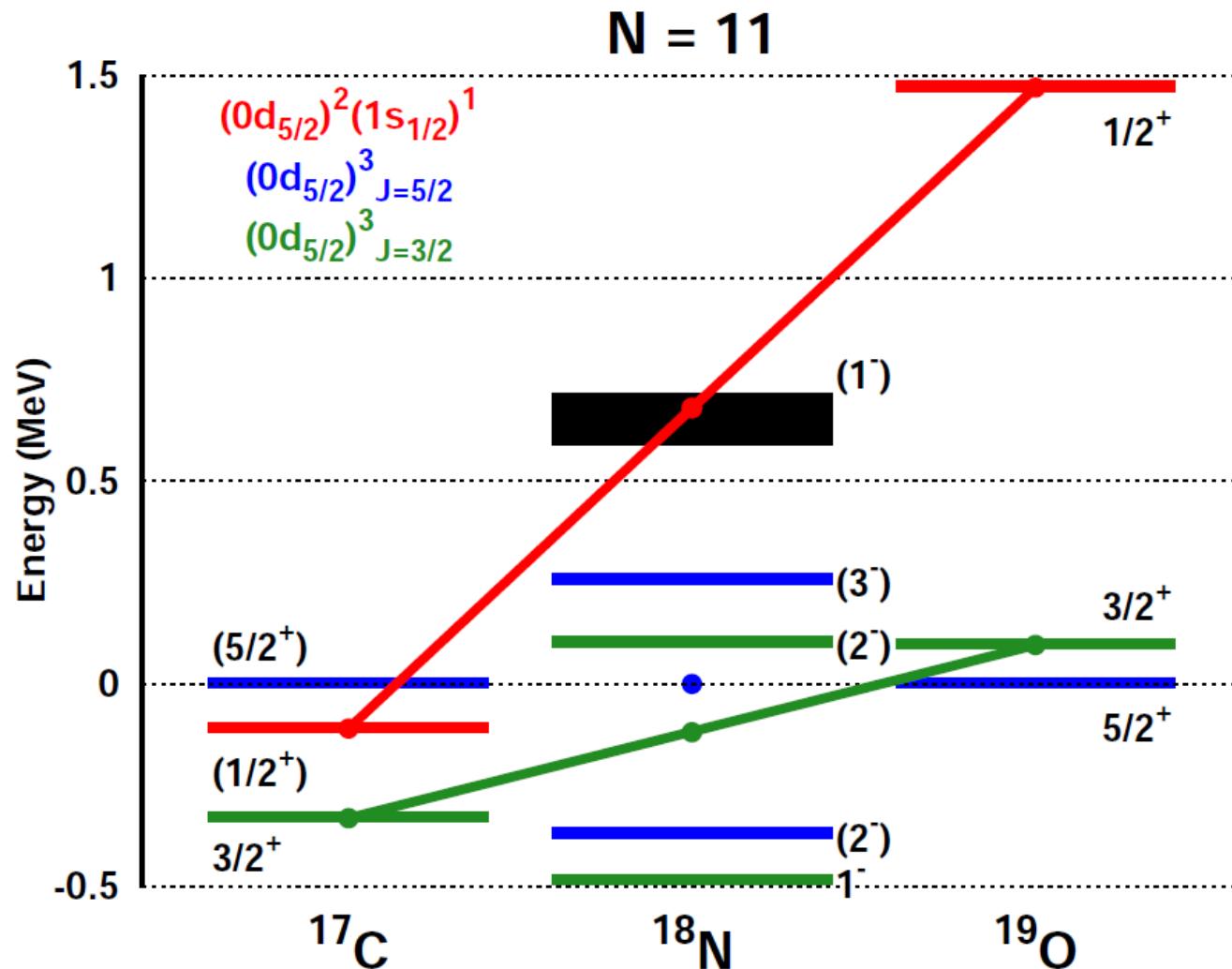
A. H. Wuosmaa et al., NIMA 580, 1290 (2007)  
J. C. Lighthall et al., NIMA 622, 97 (2010)

$$\cos\theta_{\text{c.m.}} = \frac{1}{2\pi} \frac{qeBz - 2\pi m V_{\text{c.m.}}}{\sqrt{2m E_{\text{lab}} + m^2 V_{\text{c.m.}}^2 - m V_{\text{c.m.}} qeBz/\pi}}.$$

# Preliminary $^{17}\text{N}(\text{d},\text{p})^{18}\text{N}$ results

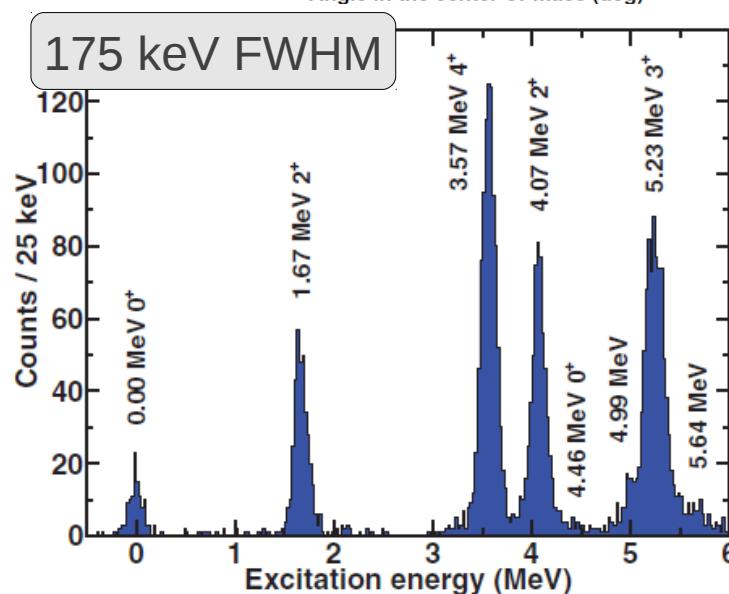
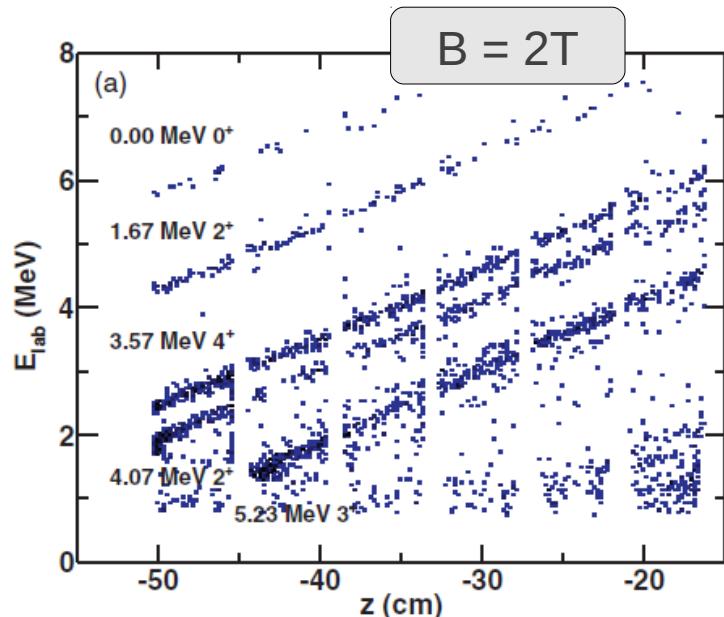
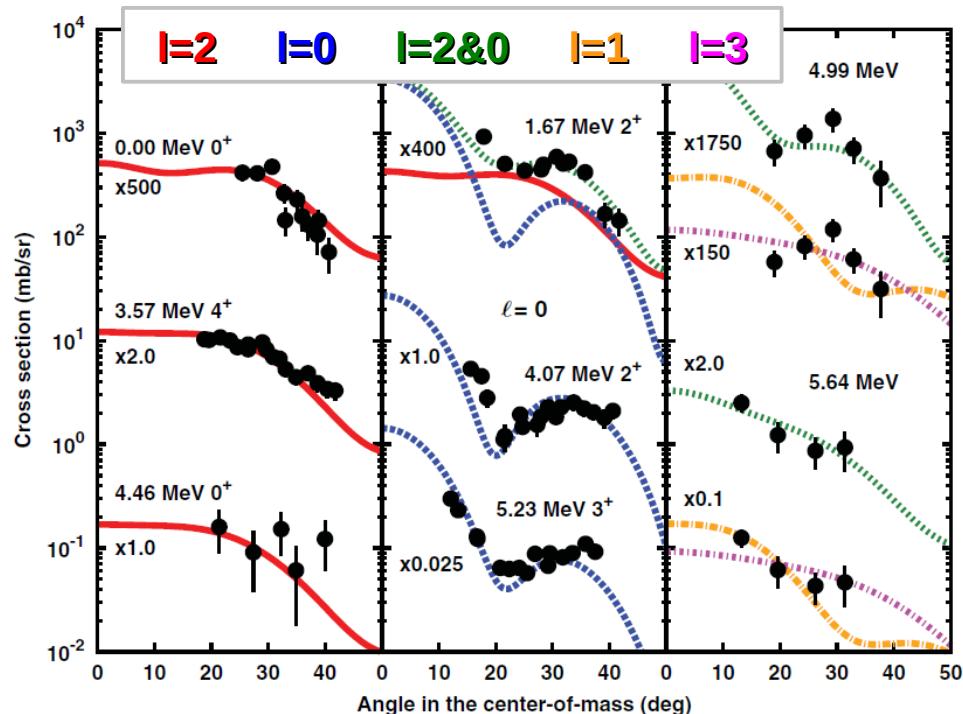


# Preliminary $^{17}\text{N}(\text{d},\text{p})^{18}\text{N}$ results



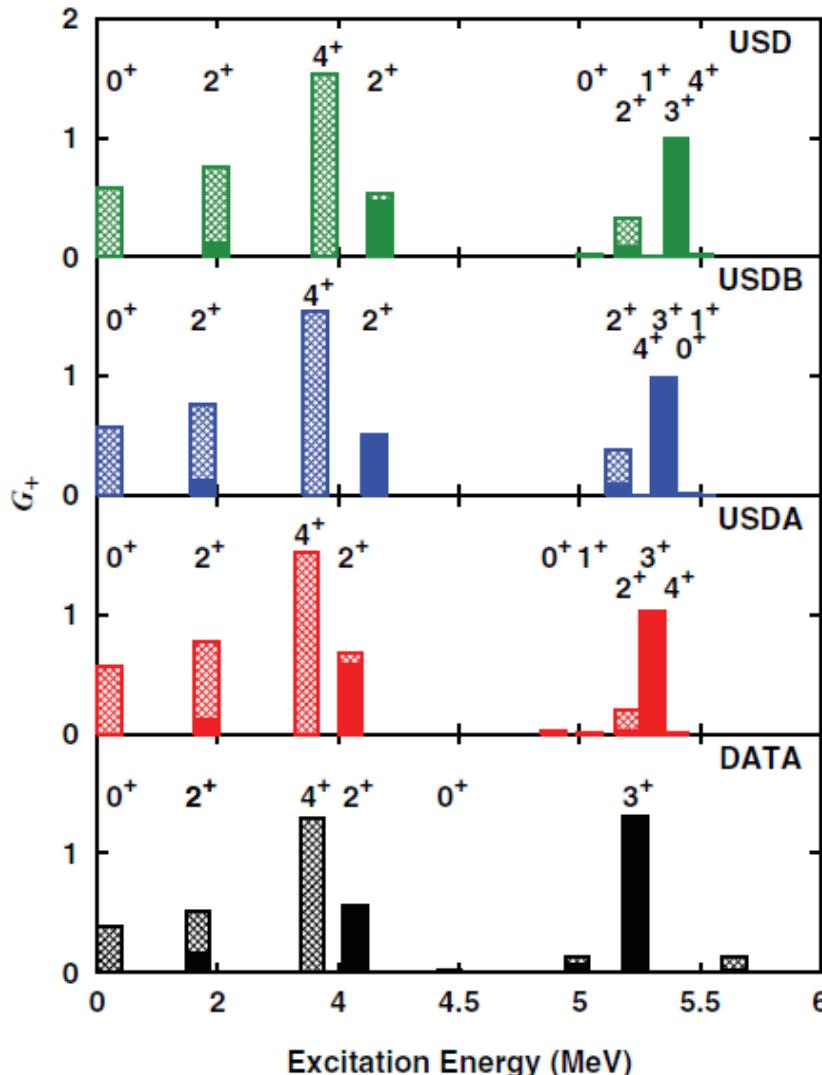
# $^{19}\text{O}(\text{d},\text{p})^{20}\text{O}$ data

- 8 states identified up to 7 MeV
- Absolute  $\sigma$  from deuteron scattering (20%)
- Angular distributions
  - Distorted wave Born approximation
  - Identified  $I = 0$   $3^+$  level at 5.23 MeV



C. M. Perey and F. G. Perey, PR 132, 755 (1963); J. P. Schiffer et al., PR 164, 1274 (1967)

# $^{19}\text{O}(\text{d},\text{p})^{20}\text{O}$ results



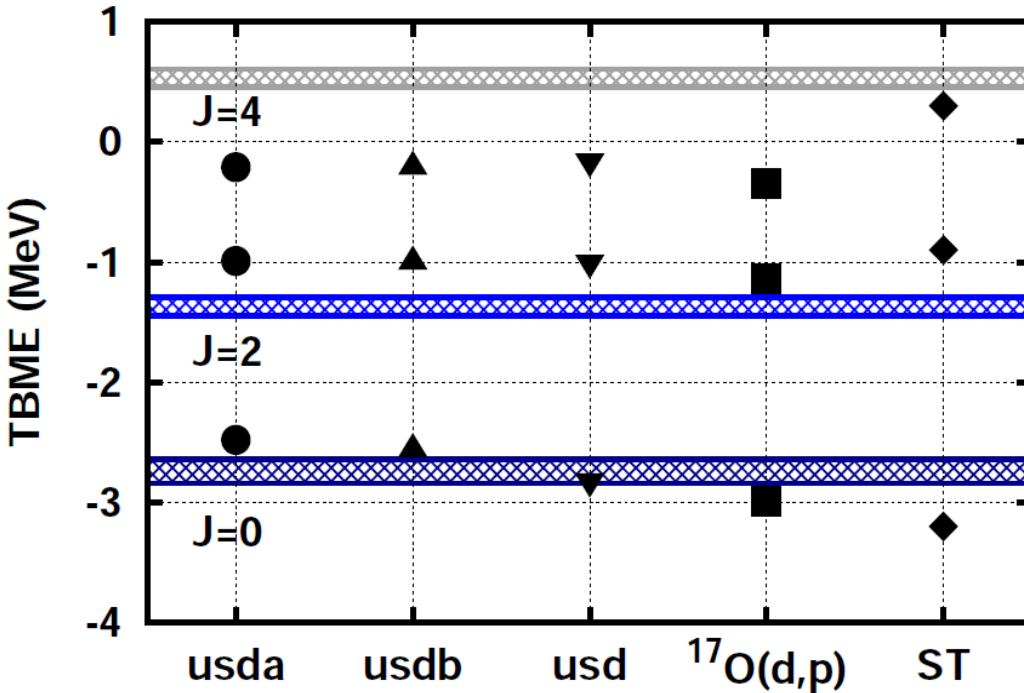
- Distorted wave analysis to extract spectroscopic factors
  - Normalized to  $^{16}\text{O}(\text{d},\text{p})^{17}\text{O}$  data
  - 30% uncertainty in total
  - 12% relative to one-another
- Checks w/ sum rules &  $^{18}\text{O}(\text{d},\text{p})^{19}\text{O}$  data
- Superb reproduction of strength by *sd* shell interactions
- Some strength to 2p-2h (1p-1h) dominated states
  - $0^+$  @ 4.46 MeV
  - 4.99 or 5.64 MeV states
- SOLID  $\rightarrow I = 0$  HATCHED  $\rightarrow I = 2$

$$G_+ = \frac{2J_f + 1}{2J_i + 1} C^2 S,$$

# Diagonal T = 1 TBME of the empirical NN interaction

- Consider  $^{20}\text{O}$  as two-neutron holes inside  $^{22}\text{O}$  ( $N = 14$   $0d_{5/2}$ ) neutron shell
  - $^{22}\text{O}$  is a good closed core
  - Most (>97%) measured strength belongs to  $0d_{5/2}$

$$E_0 = 2B[^{21}\text{O}] - B[^{20}\text{O}] - B[^{22}\text{O}] = -3.04(6) \text{ MeV}, \quad \langle (d_{5/2})^2 J | V | (d_{5/2})^2 J \rangle = E_0 + \frac{\sum (2J+1) C^2 S \cdot E^*}{\sum (2J+1) C^2 S}.$$



Agreement with trend of evaluation

Small variations between  $N = 10$  & 12

Reproduced well by  $sd$  interactions

J. P. Schiffer and W. W. True, Rev. Mod. Phys. 48, 191 (1976)  
T. K. Li et al., PRC 13, 55 (1976)

# Summary and conclusions

- Single-particle evolution in the sd shell
  - New magic numbers ( $N = 14, 16, \text{etc...}$ )
  - Quenching of traditional magic numbers ( $N = 8, 20, \text{etc...}$ )
- Strong theoretical push in the region
  - 3-nucleon forces, coupling to the continuum, components of the  $NN$  interaction (tensor force, etc...)
- Used direct reactions with HELIOS to characterize the neutron sd orbitals
  - $^{17}\text{N}(\text{d},\text{p})^{18}\text{N}$  – track evolution as a function of proton occupancy
  - $^{19}\text{O}(\text{d},\text{p})^{20}\text{O}$  – track evolution as a function of neutron occupancy
- $^{17}\text{N}(\text{d},\text{p})^{18}\text{N}$  preliminary results
  - Consistant with single-particle level assignments, candidate for  $I = 0$  level
- $^{19}\text{O}(\text{d},\text{p})^{20}\text{O}$  results
  - $0d_{5/2}$  and  $1s_{1/2}$  neutron strengths well described by sd shell model calculations
  - Extracted diagonal two-body matrix elements are in agreement with  $^{17}\text{O}(\text{d},\text{p})^{18}\text{O}$  results as well as global survey



# Acknowledgments



## The HELIOS Collaboration

B.B. Back, B.P. Kay, J.P. Schiffer, M. Albers, M. Alcorta, S. Almaraz-Calderon, S.I. Baker, S. Bedoor, P.F. Bertone, J.A. Clark, C.M. Deibel, B. DiGiovine, S.J. Freeman, J.P. Greene, J.C. Lighthall, S.T. Marley, T. Palchan-Hazan, R.C. Pardo, G. Perdikakis, K.E. Rehm, A.M. Rogers, A. Rojas, D. Santiago-Gonzalez, D.K. Sharp, D.V. Shetty, J.S. Thomas, I. Wiedenhover, and A.H. Wuosmaa

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